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How to Make Industrial Symbiosis Profitable

Mohammadtaghi Falsafi [1,2,*], Rosanna Fornasiero[1] and Umberto Dellepiane[3]

[1] ITIA-CNR Institute of Industrial Technologies and Automation,
Via Corti 12, 20133, Milan, Italy
{mohammadtaghi.falsafi, rosanna.fornasiero}@itia.cnr.it
[2] Politecnico di Milano, Department of Mechanical Engineering,
Via la Masa 1, 20157, Milan, Italy
[3] ACT Operations Research,
Via Nizza 45, 00198, Rome, Italy
umberto.dellepiane@act-OperationsResearch.com

Abstract. Industrial symbiosis can well represent a new kind of collaborative network which demands resolute attention to the flow management of materials, by-products, and waste through local and regional economies. Industrial symbiosis engages traditionally separate companies in a collaborative approach to competitive advantage involving physical exchange of different kind of products which are usually disregard by traditional market transitions. The identification of innovative models to support decision-making process in this kind of networks is urgent since it is necessary to close the loop assuring profitability at a single node as well as at system level. This paper proposes the application of the bi-level optimization model as a way to handle this two-stage problem organized into two cooperating layers. As a preliminary result, the model is applied to a simplified case where the nodes can sell their output to the market or share them in the industrial symbiosis to increase the global efficiency.

Keywords: Industrial symbiosis . Flow management . Bi-level optimization

1 Introduction

Due to the increase of production costs, organizations are becoming more concerned to find new efficient approaches. Industrial symbiosis not only reduces the supply chain costs through geographical proximity but also suggests innovative ideas to increase the income of an organization thanks to closing the loop between the output (i.e. by-products and waste of a company) to be used as input for another. Industrial symbiosis (IS) is a type of collaborative networks for regional economic relationships providing a richer, more meaningful representation of local industry drivers and regional dynamics than do traditional methods.

In this paper, it is assumed that the Production Unit (PU) is the atomic decision unit within a collaborative network and we will treat each of them as a single decision maker. Thus, we are implicitly assuming that each single PU works with a high level

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* Corresponding author

of efficiency, but this does not seem restrictive since if this is not the case, at single PU level, it is possible to optimize the planning and scheduling and increase the efficiency level. Moreover, the decision autonomy of each PU has to be maintained.

Indeed, when the PU makes a decision, it has to consider also what is happening at network level. For this reason, we can introduce the concept of upper-level decisions. They are optimized with respect to network-level KPIs (Key Performance Indicators), which in turn have a twofold purpose: from one side to increase the wealth related to a symbiotic approach at cluster level while on the other maintain the single PU decision autonomy.

In section 2, a literature overview of the recent trends in the applicability of optimization techniques in different perspectives is presented. Section 3 explains the optimization model of the problem in this paper. The application of the model in a case study and the input data and the assumptions is described in section 4. In section 5, the results of applying the model to the case study with their analyses are demonstrated. Finally, section 6 gives a brief overview of what has been done in this paper and what is going to be done to expand the model.

2 Theoretical Background

Organizations can benefit from shared resources in an IS while they can still make decisions independently. However, there are some challenging issues that prevent organizations from easily accepting to apply it. Shared resources incur some limitations for a better collaboration among organizations [1]. In addition, according to Chertow [2], the most prominent reason that many organizations are not willing to participate in IS is that they do not see sufficient material flow to make it worth wide. Chertow also emphasizes the importance of the analysis of specific industries based on key materials.

Bi-level optimization is concerned with a class of problems characterized by a particular nested structure. Some decision variables of the inner level problem may act as parameters for the objective function of the second level problem and may also influence its constraints. The nesting of these problems may be deeper and involve more than two levels, and in this case, we refer to Multilevel Programming. More in detail, a problem called lower or inner problem is nested inside the feasible region of another problem, called upper level or outer problem.

Bi-level problems, or more generally multi-level problems, allow modelling the complex situations and decision dynamics. However, their capability of capturing the complex reality results in a problem hard to solve. For this reason, a compromise between consistency with the reality and modelling simplifications is often sought.

Bi-level problems are NP-hard problems. Several approaches to solving this kind of problem have been proposed in the literature. Possible drawbacks to this formulation are:

- The problem can have large dimension, and the proposed approaches may be negatively influenced;

- To assure the convergence of an algorithm, some assumptions have to be made, and they cannot be representative of the reality we intend to model.

Why using a bi-level formulation for modelling the industrial symbiosis problem?

For answering this question, we will use a parallelism with another sector that has drawn great benefit from the development of bi-level programming. Many Transportation Management problems, in fact have been well represented with bi-level formulations. For more details, readers can refer to Marcotte (1986) or Marcotte and Marquis (1992) [3, 4].

Usually, these formulations try to model, at the inner level, the choices or the behaviors of the network users while at the upper level they represent the decision problem faced by the manager of the transport system, which wants to improve the performance of the system.

Many other applications of bi-level optimization can be found in different application fields. For example, the management and the engineering sectors also obtained advantages from this kind of optimization. In particular, in the work of Neittaanmäki and Stachurski (1992)[5], control problems with unilateral boundary-value are addressed (a typical problem with these characteristics could be represented by Optimal Shape Design problem). The bi-level structure is the result of a finite difference approximation of the original optimal control problem with boundary value. The resulting bi-level problem involves the minimization of a functional (different according to the particular problem) that depends on control variables and state variables. The state variables are the solution of an auxiliary quadratic problem which is characterized by parameters that depend on the control variables. Some features of this problem are the expensiveness of the functional evaluation and the large scale of the inner level problem. It is important to stress that these features are often common in many real two-level problems.

Indeed, an important motivation for the widespread use of bi-level models in the management field is the consistent presence of decentralized decision-making processes. This kind of decisions is particularly common within companies where different choices, which will affect each other, are taken by different parties in some points of the supply chain. Two papers which deal with decentralized decision process in supply chain are [Patriksson and Wynter (1999) [6] and Júdice and Faustino (1988) [7].

Recently bi-level applications have also appeared in financial studies, and examples can be found in the works of Carriòn et al. (2009) [8] and Conn and Vicente (2012) [9].

Another Network Design problem has been faced in Ben-Ayed et al. (1992) [10] where the upper-level decision maker (the manager of the system) would like to allocate some investments to strengthen an existent interregional highway network. Choosing an investment allocation, the manager of the system changes the users' preferences. In consistence with this dynamic, the users are the inner-level decision makers who have the goal of minimizing their travel costs.

Furthermore, to answer the previous question, we need to report also two important assumptions that we cannot relax:

1. each single PU works with a high level of efficiency
2. the decision autonomy of each PU has to be maintained

Focusing on the last example and considering that the following assumptions cannot be relaxed, we understand the reason of the use of bi-level programming for modelling the symbiosis problem.

First of all, the inner level of the problem is the decisions related to the single Production Units (PUs) within each plant. These are optimized with respect to some proper KPIs. In this study, we will assume that the PUs are the atomic decision units within a collaborative network and we will treat each of them as a single decision maker.

Indeed, it is necessary to consider what happens at the network level. For this reason, we can introduce the concept of the upper-level decisions. These are optimized with respect to network-level KPIs, which in turn have a twofold purpose: from one side to increase the wealth related to a symbiotic approach while on the other maintain the single PU decision autonomy.

In order to make things work, coordination to improve the whole symbiotic network performance is necessary, measured in different ways, for example economic (profit or costs), environment impact (energetic, waste) or social. This coordination is provided by an organization that is a physical organization or more easily a virtual platform which is called the network coordinator. Of course, for maintaining the decision autonomy of each PU, a top-down approach (i.e. a centralized network coordinator) cannot be considered.

We then conceive a multi-layer architecture organized into two cooperating layers. At the company level, each industry performs its Supply Chain Optimization (SCO) to gain a high efficiency operative level optimizing its short-term and long-term decisions. These decisions do not take into account any of the decisions of the other industries in the cluster or in other words, are completely independent. To govern the whole cluster performance, we introduce the cluster-level optimization, whose aim is the increasing of the global cluster efficiency. This two-layer architecture is formulated by a bi-level optimization problem.

3 Methodology

The objective of the model is to integrate the two decision levels: decisions at PU level for managing flows in supply chain and at the network level for managing the industrial symbiosis (IS) among PUs. The aim of the model is to support the optimization of the flow in the cluster (IS) while maximizing the total benefit of each PU and dynamically maximize the benefit for the IS. Accordingly, the upper level of the bi-level model maximizes the total flow inside the IS among PUs, and the inner level maximizes the total benefit of each of the PUs.

Input parameters

i	*Index for PU under consideration where* $i = 1,2,..,S$
j	*Index for PU other than considered PU where* $j = 1,2,..,S-1$ *where* $j \neq i$
k_i	*Index for finished products at each PU i where* $k_i = 1,2,..,K_i$
b_i	*Index for by − products at each PU i where* $b_i = 1,2,..,B_i$
w_i	*Index for waste products at each PU i where* $w_i = 1,2,..,W_i$

l_i	*Index for materials purchased from market by PU i where* $l_i = 1,2,..,L_i$
mkt	*Index for market*
IS	*Index for industrial symbiosis cluster*
SA	*Index for standalone mode for each PU*
op	*Index for output products*
ip	*Index for input products*
P	*Index for product, regardless if it is output or input of a PU*
s	*Set of PUs for IS where* $s = 1,2,..,S$
SP_{op}^{i}	*Selling price of output products op sold by PU i*
PC_{op}^{i}	*Production cost of output products op produced at PU i*
C_{ip}^{i}	*Cost of purchasing input products ip by PU i*
$CT_{w_i}^{i}$	*Cost of disposing waste* w_i *at PU i*
d_p^{mkt}	*Market demand for product p at PU i*
$PCap_{op}^{i}$	*Production capacity of final products at PU i*
$ICap_{ip}^{i}$	*Inventory capacity of input products ip at PU i*
$ICap_{op}^{i}$	*Inventory capacity of output products op at PU i*
H_{ip}^{i}	*Inventory holding cost of input products ip at PU i*
H_{op}^{i}	*Inventory holding cost of output products op at PU i*
$I_{ip}^{i,0}$	*Initial inventory level of input products ip at PU i*
$I_{op}^{i,0}$	*Initial inventory level of output products op at PU i*

The assumption is that finished products and by-products could be sold to both the market and other PUs in the IS with the same price ($i.e. SP_{op\in k_i}^{i}, SP_{op\in b_i}^{i}$). Also, the price and purchasing cost for a specific material is the same for all the PUs. The waste is normally disposed with the cost $CT_{w_i}^{i}$, while it could be exchanged in the IS without any cost ($SP_{op\in w_i}^{i} = 0, C_{ip\in w_j}^{i} = 0$).

The inventory level of each PU is the input inventory for input products and output inventory for output products. For each of them we assume an initial inventory level (i.e. $I_{ip}^{i,0}$ and $I_{op}^{i,0}$).

For each product, there is a specific demand in the market (d_p^{mkt}). This is a general demand regardless of the product type (finished product, by-product) of each PU. In other words, if two PUs produce the same product (finished product or by-product), the market demand of that product for both of them is the same.

Decision variables (Positive)

X	*Amount of goods from/to the market*
Y	*Amount of goods from/to the IS*
W	*Amount of waste disposed*
I	*Final inventory level*

W is the proportion of waste which is disposed. The remaining proportion is transacted in the IS with the other PUs.

1. Upper Level Objective Function

$$\mathrm{Max}\, Z = Max \sum_{i\in IS} \sum_{j\in\{IS\setminus i\}} Y_{p}^{i,j}$$

The objective function of the upper level maximizes the total flow inside IS.

2. Balance of demand

$$\sum_{i\in IS} X_{op\in k_i\cup b_i}^{i,mkt} \le d_{p}^{mkt} \qquad \forall i \in 1,2,\dots,S$$

3. Balance of production capacity

$$\sum_{j\{IS\setminus i\}} Y_{op}^{i,j} + X_{op}^{i,mkt} + I_{op}^{i} - I_{op}^{i,0} \le PCap_{op\in k_i}^{i} \qquad \forall i \in 1,2,\dots,S$$

4. Balance of output products

$$\sum_{j\{IS\setminus i\}} Y_{op}^{i,j} + X_{op}^{i,mkt} + I_{op}^{i} - I_{op}^{i,0} = f_i \left(\sum_{j\{IS\setminus i\}} Y_{op\in k_i}^{i,j} + X_{op\in k_i}^{i,mkt} + I_{op\in k_i}^{i} - I_{op\in k_i}^{i,0} \right) \quad \forall i \in 1,2,\dots,S$$

5. Balance of input products

$$\sum_{j\{IS\setminus i\}} Y_{ip}^{i,j} + X_{ip}^{i,mkt} + I_{ip}^{i} - I_{ip}^{i,0} = h_i \left(\sum_{j\{IS\setminus i\}} Y_{op\in k_i}^{i,j} + X_{op\in k_i}^{i,mkt} + I_{op\in k_i}^{i} - I_{op\in k_i}^{i,0} \right) \quad \forall i \in 1,2,\dots,S$$

6. Balance of input inventory capacity

$$I_{ip\in l_i}^{i} \le ICap_{ip\in l_i}^{i} \qquad \forall i \in 1,2,\dots,S$$

7. Balance of output inventory capacity

$$I_{op}^{i} \le ICap_{op}^{i} \qquad \forall i \in 1,2,\dots,S$$

8. Inner Level Objective Function - Maximization of the profit of each PU independently from the IS

$$
\begin{aligned}
Max\ Z_i = & \sum_{op\in k_i \cup b_i} \left\{ (SP_{op}^{i} - PC_{op}^{i}) \times \left(X_{op\in k_i}^{i,mkt} + \sum_{j} Y_{op\in k_i}^{i,j} \right) \right\} \\
& - \sum_{ip\in l_i} \left\{ C_{ip}^{i} \times \left(X_{ip}^{mkt,i} + \sum_{j} Y_{ip}^{j,i} \right) \right\} - \sum_{w_i} \left(CT_{w_i}^{i} \times W_{w_i}^{i} \right) - \sum_{ip\in l_i} (H_{ip}^{i} \times I_{ip}^{i}) \\
& - \sum_{op\in k_i \cup b_i} (H_{op}^{i} \times I_{op}^{i}) \qquad \forall i \in 1,2,\dots,S
\end{aligned}
$$

a) Balance of demand

$$\sum_{i\in IS} X_{op\in k_i \cup b_i}^{i,mkt} \le d_{p\in k_i \cup b_i}^{mkt} \qquad \forall k_i, b_i$$

b) Balance of production capacity

$$\sum_{j\{IS\backslash i\}} Y_{op}^{i,j} + X_{op}^{i,mkt} + I_{op}^{i} - I_{op}^{i,0} \le PCap_{op\in k_i}^{i} \qquad \forall k_i$$

c) Balance of output products

$$\sum_{j\{IS\backslash i\}} Y_{op}^{i,j} + X_{op}^{i,mkt} + I_{op}^{i} - I_{op}^{i,0} = f_i \left(\sum_{j\{IS\backslash i\}} Y_{op\in k_i}^{i,j} + X_{op\in k_i}^{i,mkt} + I_{op\in k_i}^{i} - I_{op\in k_i}^{i,0} \right) \quad \forall b_i, w_i$$

d) Balance of input products

$$\sum_{j\{IS\backslash i\}} Y_{ip}^{i,j} + X_{ip}^{i,mkt} + I_{ip}^{i} - I_{ip}^{i,0} = h_i \left(\sum_{j\{IS\backslash i\}} Y_{op\in k_i}^{i,j} + X_{op\in k_i}^{i,mkt} + I_{op\in k_i}^{i} - I_{op\in k_i}^{i,0} \right) \qquad \forall ip$$

e) Balance of input inventory capacity

$$I_{ip\in l_i}^{i} \le ICap_{ip\in l_i}^{i} \qquad \forall ip$$

f) Balance of output inventory capacity

$$I_{op\in k_i \cup b_i}^{i} \le ICap_{op\in k_i \cup b_i}^{i} \qquad \forall k_i, b_i$$

4 Illustrative Example

The above model has been applied to a simplified example of an IS case with five PUs, and it is partially taken from the paper of Gonela and Zhang (2014) [11]. Each PU produces a set of finished products, by-products, and wastes. It is assumed that the waste is either disposed or transacted inside the IS among PUs. Furthermore, for some products, there is the possibility to transact with one or more PUs as well as the market, while some products could solely be purchased/sold to the market. Figure 1 shows the schema of the PUs and the potential interconnections among them. For each potential product, it is also specified if it is a finished product (FP), by-product (BP), or waste (W).

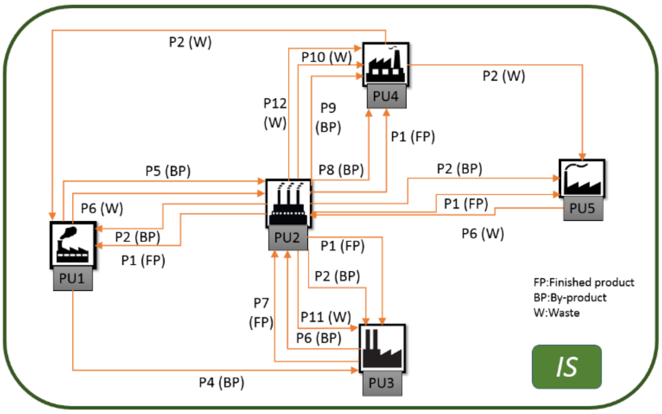

Fig. 1. Schematic view of PUs and potential interconnections

Table 1 shows the input data for the first two PUs. For each PU, it is considered a set of inputs (*ip*) that could be supplied from the market or, potentially, from the PUs in the network. The purchasing cost is the same if the product is supplied from the market or it is a finished product or by-product of another PU inside the IS ($C^{i}_{ip\in l_i \cup k_j \cup b_j}$). Alternatively, if the input product is a waste of another PU inside the IS, it is transacted without any cost ($C^{i}_{ip\in w_j} = 0;\ \forall w_j$). For producing each unit of finished product, a specific amount of each input product is consumed and a specific amount of by-product and waste is produced. Hence, it is defined by a coefficient which is specified in parenthesis in the column *ip* and *op*.

The three types of outputs are finished products, by-products, and waste. Finished product is the main output of the PU. For each PU, there are also one or more by-products and wastes. Based on the configuration of the PU, it is capable of producing a certain amount of finished product ($PCap^{i}_{op\in k_i}$). All the other parameters are the same as is explained in section 3. There are some products for which some dimensions are not applicable (n.a.). For example, in case of P1 (which could represent electricity) it is not possible to keep inventory for it.

5 Results and Discussion

Table 2 shows the first part of the results from applying the bi-level optimization. The decision variables are the flows to/from the market, the wastes that are disposed, and the final inventory level. The numbers in green represent the flows for each PU. For instance, the product P12 ($X_{P12}^{mkt,i}$) is the input for PU 4 and therefore, it is possible to have a flow greater than zero which is 2412. The results also show that some products do not interact with the market when considering the IS. For example, the output product P2 from PU 2 does not have any interaction with the market. In other words, it is entirely transacted within the IS.

Table 1. Input data

i	ip	$C^i_{ip\in l_i\cup k_j\cup b_j}$	$C^i_{ip\in w_j}$	H^i_{ip}	$ICap^i_{ip}$	$I^{i,0}_{ip}$
1	P1 (0.5)	5	n.a.	n.a.	n.a.	n.a.
	P2 (2)	3	0	n.a.	n.a.	n.a.
2	P5 (50)	1.5	n.a.	0.55	200	20
	P7 (1)	4	n.a.	1	5	2
	P6 (30)	0.02	0	n.a.	n.a.	n.a.

i	op			$PC^i_{op\in k_i}$	SP^i_{op}	PC^i_{op}	$CT^i_{w_i}$	H^i_{op}	$ICap^i_{op}$	$I^{i,0}_{op}$	d^{mkt}_p
	k_i	b_i	W_i								
1	P3			60	13	10		1	0.5	0	70
		P4 (0.5)			2.5	1		0.02	1	0.2	100
		P5 (30)			1.5	0.5		0.5	15	5	1500
			P6 (30)		0	0	0.002	n.a.	n.a.	n.a.	0
2	P1			99	5	4		n.a.	n.a.	n.a.	110
		P2 (1)			3	1		n.a.	n.a.	n.a.	90
		P8 (30)			1	0.5		n.a.	n.a.	n.a.	4000
		P9 (50)			2.2	0.5		0.2	300	50	10000
			P10 (10)		0	0.5	1	n.a.	n.a.	n.a.	0
			P11 (10)		0	0	0.75	n.a.	n.a.	n.a.	0
			P12 (12)		0	0	0.005	n.a.	n.a.	n.a.	0

Figure 2 shows the flows between PUs inside IS. For example, 90 units of finished product P1 which is produced by PU 2, goes to the market and 4 and 5 units is sold to PUs 1 and 3 respectively. However, there is no transaction with the other potential PUs (i.e. 4,5). So, production amount of P1 in PU 2 is 99 units.

Table 2. Optimization results – Flow from/to the market, amount of waste disposed, and Inventory level

Decision variable	PU (i)					Decision variable	PU (i)				
	1	2	3	4	5		1	2	3	4	5
$X_{P8}^{mkt,i}$	0	0	0	0	0	$X_{P8}^{i,mkt}$	0	1100	0	0	0
$X_{P7}^{mkt,i}$	0	85	0	0	0	$X_{P7}^{i,mkt}$	0	0	90	0	0
$X_{P4}^{mkt,i}$	0	0	12.8	0	0	$X_{P13}^{i,mkt}$	0	0	0	360	0
$X_{P1}^{mkt,i}$	26	0	0	144	14.3	$X_{P4}^{i,mkt}$	0	0	0	0	0
$X_{P11}^{mkt,i}$	0	0	0	0	0	$X_{P1}^{i,mkt}$	0	90	0	0	0
$X_{P9}^{mkt,i}$	0	0	0	0	0	$X_{P3}^{i,mkt}$	60	0	0	0	0
$X_{P5}^{mkt,i}$	0	2965	0	0	0	$X_{P9}^{i,mkt}$	0	3190	0	0	0
$X_{P2}^{mkt,i}$	0	0	0	0	0	$X_{P5}^{i,mkt}$	0	0	0	0	0
$X_{P10}^{mkt,i}$	0	0	0	720	0	$X_{P14}^{i,mkt}$	0	0	0	0	140
$X_{P12}^{mkt,i}$	0	0	0	2412	0	$X_{P2}^{i,mkt}$	0	0	0	0	0
$X_{P6}^{mkt,i}$	0	0	0	0	0	W_{P11}^{i}	0	935	0	0	0
$I_{P8}^{i}\ (ip)$	0	0	0	0	0	W_{P2}^{i}	0	0	0	35.4	0
$I_{P7}^{i}\ (ip)$	0	5	0	0	0	W_{P10}^{i}	0	0	0	0	0
$I_{P4}^{i}\ (ip)$	0	0	10	0	0	W_{P12}^{i}	0	0	0	0	0
$I_{P11}^{i}\ (ip)$	0	0	0	0	0	W_{P6}^{i}	45	0	0	0	0
$I_{P4}^{i}\ (ip)$	0	0	0	0	0	$I_{P7}^{i}\ (op)$	0	0	0	0	0
$I_{P4}^{i}\ (ip)$	0	200	0	0	0	$I_{P4}^{i}\ (op)$	0	0	0	0	0
$I_{P4}^{i}\ (ip)$	0	0	0	110	0	$I_{P3}^{i}\ (op)$	0	0	0	0	0
						$I_{P9}^{i}\ (op)$	0	300	0	0	0
						$I_{P5}^{i}\ (op)$	0	0	0	0	0
						$I_{P14}^{i}\ (op)$	0	0	0	0	5

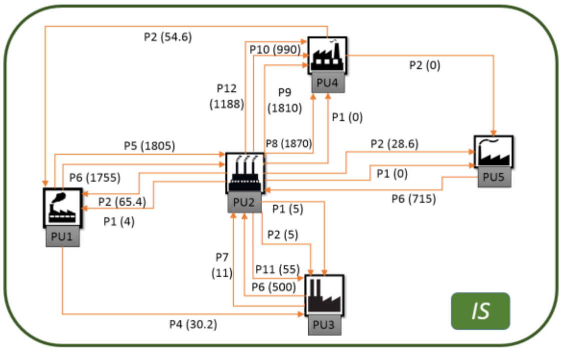

Fig. 2. Optimization results – Flows to the other PUs inside IS

Table 3 compares the results when the PUs operate as standalone and independently from the IS (SA) with the results obtained by the bi-level optimization in the IS. In other words, the standalone mode is the result of the inner function when the transaction flows within the cluster is set to zero (Y=0). In the standalone mode, production units 1,2,3, and 5 produce less than their production capacity (i.e. 60,99,150 and 100 respectively) to maximize their profit. Contributing with the cluster, the PUs 1,2, and 3 produce with the maximum production capacity, and therefore their utilization arrives at 100%. This difference stems from the fact that collaborating in the IS, companies can produce more than the market demand and transact the additional production within the cluster.

Regarding the economic impact, there is an increase in four PUs. The companies with more collaboration with the IS observe more increase in their profits. As Figure 2 represents, most of the connections in the cluster are related to PU 2. Consequently, this PU has the highest profit increase with around 42%. The increase of the profit is due to the free transaction of waste inside the IS while it is costly for the PU to dispose them. On the contrary, PU 5 with the lowest symbiotic interaction, its profit decreases slightly to approximately 4%.

Table 3. Impacts of the model

PU	Production capacity	Production SA	Utilization SA %	Profit SA	Production IS	Utilization IS %	Profit IS	Profit difference %
1	60	49.83	83	1,260.6	60	100	1,684	+ 14.4
2	99	90	91	777.6	99	100	1,926.8	+ 42.5
3	100	89	89	124.2	100	100	155.3	+ 11.1
4	360	360	100	4,665.7	360	100	5,564.7	+ 8.8
5	150	138	92	128.2	143	95	117.7	- 4.3

6 Conclusion

The emergence of environmental and sustainability regulations is asking companies to define new collaboration mechanisms to close the loop of waste and by-product and to put them back into the system as an input for other companies. IS is one of the sustainable strategies that can help to reduce waste production and logistic costs. In IS, traditionally separate plants collocate in order to efficiently utilize resources, reduce waste and increase profits for the entire system as well as each player in the IS. This paper focuses on developing an innovative approach for supporting the definition of the IS configurations based on the total profit and on the profit of each PU.

An innovative decision framework that combines two decision levels is proposed to determine the optimal configuration of IS and to design the optimal network flows of various products in the network. An empirical case has been conducted to study the efficiency and effectiveness of the proposed model, and the results suggest a significant increase in profitability for the single nodes and the rest of the players in the network when IS is applied. In this case, the collaboration is based on the possibility to share resources as a way to gain profit for all the partners in the network. The model is still under development and will be further improved introducing other decision variables (e.g. transportation costs) and enlarging the case study to a larger network.

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